Composite Higgs searches

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'Next steps in the Energy Frontier - Hadron Colliders' workshop

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Introduction

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After the full LHC program we will gain a lot of information

- fair determination of single **Higgs observables** ($\sim 10\%$)
- test of **naturalness** up to $\mathcal{O}(few\%)$

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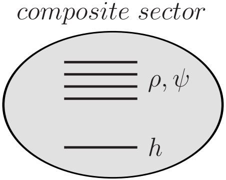
➢ Which is the situation in composite Higgs models?

Introduction: the composite Higgs scenario

In composite Higgs models the Higgs arises as a bound state of a **new strongly-coupled sector**

The composite dynamics gives rise to additional states at the TeV scale:

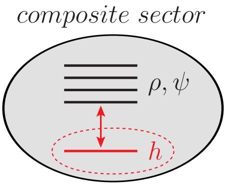
- Fermionic top partners
- Spin-1 resonances
  (KK-gluons and EW resonances)



Introduction: the composite Higgs scenario

Need **mass gap** between the Higgs and the other composite states

➢ natural if the Higgs is a **Goldstone**



Key features:

- Modification of the SM Higgs couplings
- Non-linear dynamics ➠ new non-renormalizable interactions

Introduction

Indirect bounds and lack of enough luminosity limit some important searches at the LHC:

- EW precision data strongly favor small deviations in the **linear Higgs couplings** ($< 10\%$)
- EW precision data push the mass of **vector resonances** to the multi-TeV range
- tests of the **non-linear Higgs dynamics** usually rely on rare processes with small cross sections

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➢ What kind of new experiments do we need to extend our reach on composite models?

Introduction

In this talk I will discuss how much a future $100\ \mathrm{TeV}$ hadronic collider could improve our reach on the parameter space of composite Higgs scenarios:

- testing the Higgs compositeness
- searching for top partners
- searching for vector resonances

Testing Higgs compositeness

Higgs compositeness

The **Goldstone boson nature** of the Higgs implies a well defined pattern of deformations of the Higgs couplings

$$\mathcal{L} = m_W^2 W_\mu^+ W^{-\mu} \left(1 + 2\, k_v \frac{h}{v}\right) - \sum_\psi m_\psi \overline{\psi}\psi \left(1 + k_f \frac{h}{v}\right) + h.c.$$

❖ size of the corrections controlled by the compositeness scale f

- The couplings to the gauge fields only depend on the Goldstone structure (eg. $SO(5) \to SO(4)$)

$$\mathrm{MCHM}_4,\ \mathrm{MCHM}_5 \qquad \kappa_v = \sqrt{1-\xi} \qquad \xi = v^2/f^2$$

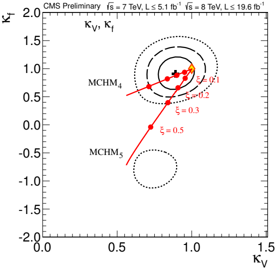
- The couplings to the fermions have more model dependence

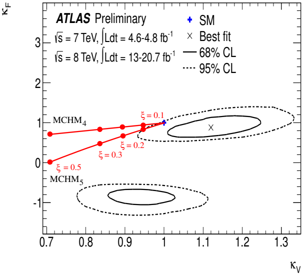
$$\begin{aligned} \mathrm{MCHM}_4 \qquad & k_f = \sqrt{1-\xi} \\ \mathrm{MCHM}_5 \qquad & k_f = \frac{1-2\xi}{\sqrt{1-\xi}} \end{aligned} \qquad \xi = v^2/f^2$$

Single Higgs couplings

Measuring κ_v gives a **model-independent** bound on ξ

The current data give a bound $\xi \lesssim 0.2$





- ➢ The ultimate LHC reach is $\xi \sim 0.1$
- ➢ **Limited improvement** possible at an hadronic machine!

Higgs couplings at a 100 TeV machine

Other measurements can however benefit from high energy and high luminosity:

- Higgs coupling to the **top quark**
- **non-linear** Higgs interactions

Possible relevant channels:

➢ WW scattering and $WW \to hh$

➢ Double Higgs production in gluon fusion

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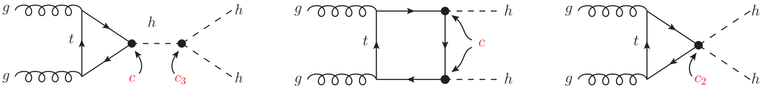
Double Higgs production in gluon fusion

The relevant Higgs couplings can be parametrized as

$$m_{top}\,\bar{t}t\left(c\,\frac{h}{v}+\frac{c_2}{2}\,\frac{h^2}{v^2}\right)\,,\qquad c_3\,g_{hhh}^{SM}\,h^3$$



- ➢ can be used to extract the Higgs trilinear coupling c_3

[Baur, Plehn, Rainwater; Grober, Muhlleitner; Contino, Ghezzi, Moretti, G. P., Piccinini, Wulzer; Dolan, Englert, Spannowsky; Goertz, Papaefstathiou, Yang, Zurita; ...]

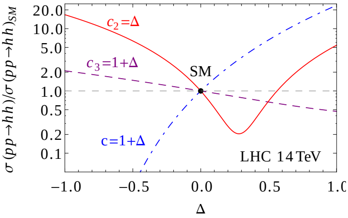
- ➢ is sensitive to **non-renormalizable Higgs interactions** ($\bar{t}thh$ is a distinctive sign of a composite Higgs)

[Grober, Muhlleitner; Contino, Ghezzi, Moretti, G. P., Piccinini, Wulzer]

Double Higgs production in gluon fusion

The cross section can be significantly **modified** even for small deviations of the Higgs couplings

- ➢ strong dependence on c and c_2
- ➢ milder dependence on c_3



At the LHC the measurement is severely limited by statistics:

$$\sigma(gg \to hh \to \gamma\gamma bb)_{SM} \simeq 5\,\mathrm{ab} \ @ \ 14\,\mathrm{TeV}$$

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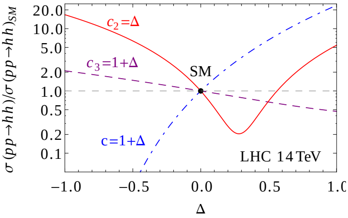
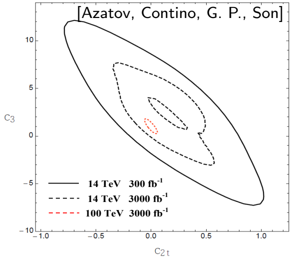


At the LHC the measurement is severely limited by statistics:

$$\sigma(gg \to hh \to \gamma\gamma bb)_{SM} \simeq 5\,\text{ab} \text{ @ } 14\,\text{TeV} \;\; ➠ \;\; 200\,\text{ab} \text{ @ } 100\,\text{TeV}$$

- ➢ **huge improvement** at 100 TeV!

Can test Higgs trilinear and Higgs compositeness for $\xi \sim 0.02$

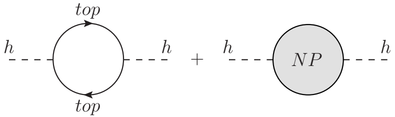


Searches for top partners

Top partners and naturalness

Top partners control the generation of the Higgs potential and the stability of the Higgs mass

$$\delta m_h^2\big|_{1-loop} \sim$$



$$\sim -\frac{y_{top}^2}{8\pi^2} M_X^2 \lesssim \mathrm{TeV}$$

A **bound** on the partners mass translates into an unavoidable amount of **fine-tuning**

$$\Delta \gtrsim \left(\frac{M_X}{400\ \mathrm{GeV}}\right)^2$$

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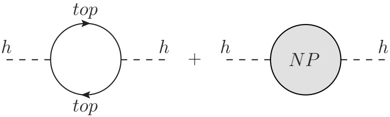

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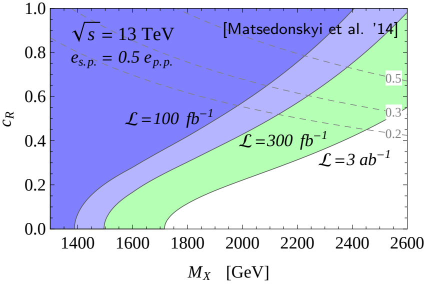
Natural Composite Higgs: light top partners $\Leftrightarrow$ **Natural SUSY**: light stops

Top partners at the LHC

Top partners can be easily produced through:

- QCD interactions (pair prod. – universal)
- couplings with heavy quarks (single prod. – model dependent)

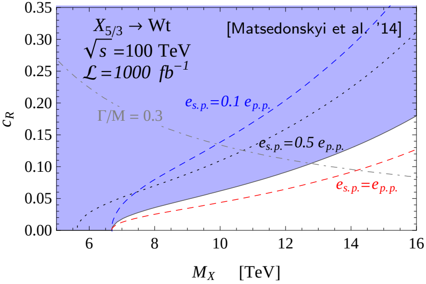


➢ LHC can probe partner masses up to $M_X \sim 2$ TeV

➢ testing **naturalness** up to $\mathcal{O}(4\%)$

Top partners at 100 TeV

At 100 TeV the production cross section allows to explore a huge range of masses



- ➢ model-independent reach $M_X \sim 7$ TeV
- ➢ by using single production $M_X \sim 12$ TeV
- ➢ testing **naturalness** up to $\mathcal{O}(0.1\%)$

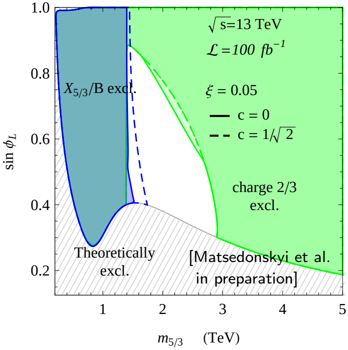
Implications on explicit models

In a large class of models (eg. $\mathrm{MCHM}_{4,5,10}$) the mass of the lightest partner is tightly connected to the compositeness scale

[Matsedonskyi, G. P., Wulzer; Marzocca, Serone, Shu; Pomarol, Riva]

$$\frac{m_H}{m_{top}} \gtrsim \frac{\sqrt{3}}{\pi}\frac{M_X}{f} \quad \Rightarrow \quad \xi \lesssim \left(\frac{500\ \mathrm{GeV}}{M_X}\right)^2$$

- ➢ LHC can test $\xi \sim 0.05$
- ➢ at 100 TeV can probe $\xi \sim 0.002$



Searches for vector resonances

Vector resonances

Vector resonances are unavoidably present in composite Higgs models

The composite dymanics is charged under an extension of the SM gauge groups

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- EW vector resonances

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EW vector resonances

EW vector resonances are mixed with the SM gauge bosons and generate corrections to the EW observables

$$\Delta\widehat{S} \simeq \frac{m_W^2}{m_\rho^2}$$

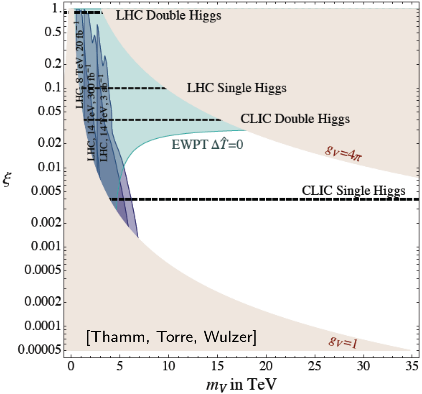
The EW precision data put strong (indirect) bounds

$$m_\rho \gtrsim 2\ \mathrm{TeV}$$

- Much stronger bound if no tuning in $\widehat{T}$: $m_\rho \gtrsim 5\ \mathrm{TeV}$

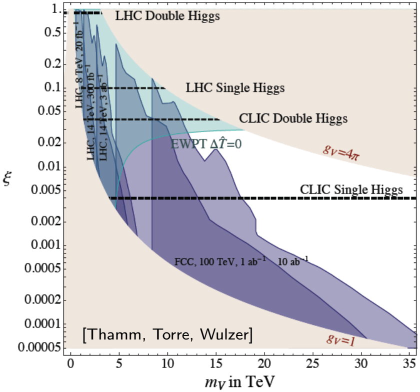
EW vector resonances

- most of the parameter space accessible at the LHC is already **disfavored** by the EW data



EW vector resonances

- most of the parameter space accessible at the LHC is already **disfavored** by the EW data
- an $100\ \mathrm{TeV}$ collider can easily probe regions with **tiny Higgs compositeness** ($\xi \lesssim 0.002$)



Conclusions

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Thanks to the large increase in energy and cross sections a future $100\ \mathrm{TeV}$ hadronic collider can hugely improve the searches for composite Higgs scenarios

➢ Significantly **extend** LHC searches

- reach top partners with $M_X \sim 10\ \mathrm{TeV}$
- test naturalness up to $\mathcal{O}(0.1\%)$

➢ **Probe** observables and dynamics not testable at the LHC

- non-linear Higgs couplings
- EW vector resonances